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A Technical Publication Devoted to the Selection and Use of Lubricants

THIS ISSUE

LOW TEMPERATURE HYDRAULIC OPERATIONS

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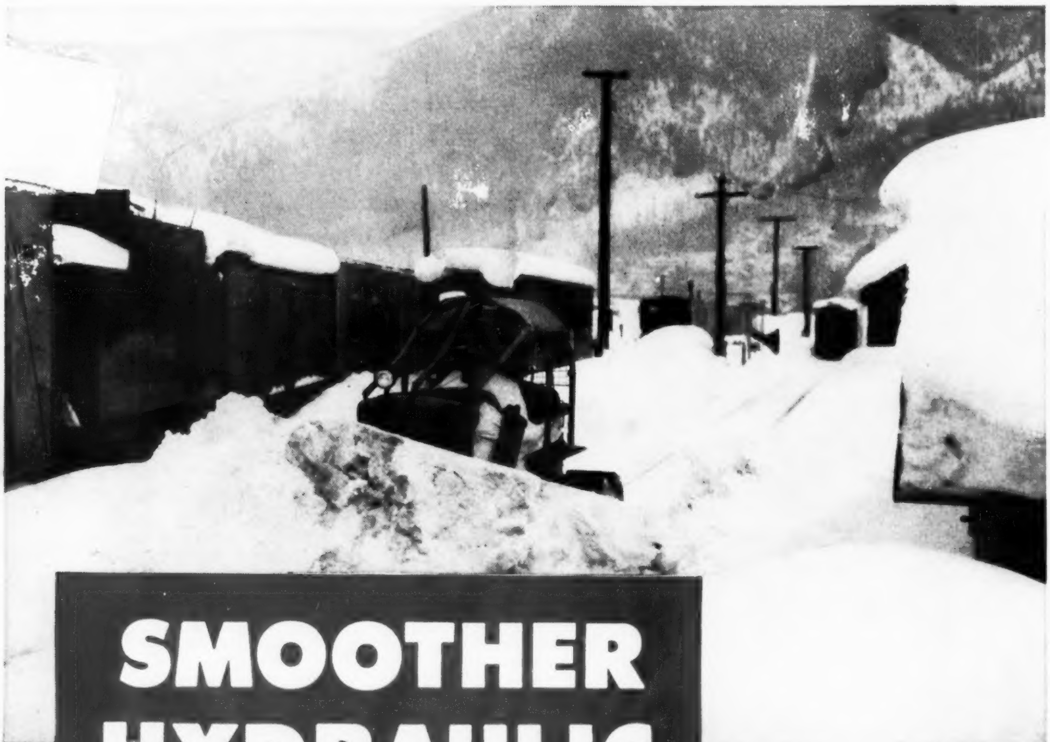

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Low Temperature Hydraulic Operations

Modern cranes, bulldozers, tractors, snowplows and lifts have become dependent upon hydraulic power rather than mechanical linkages as a means for motivating many of their working parts. The reason for this is that hydraulic devices may be more conveniently and economically adapted to machinery of this type because of their lesser bulk per unit of work required, and because their installation is much simpler and more flexible than are mechanical contrivances which achieve the same purposes.

Most of the outdoor hydraulic equipment is subjected to wider ranges of operating temperature than indoor machine tool circuits. Construction or mining equipment is exposed to ambient temperatures of 110°F. and higher in tropical climates, while the same type of equipment may be required to operate at ambients of minus 30°F. or below in the Far North. Under these temperature extremes the quality and type of hydraulic oil used become major factors in the success of equipment operation.

In hot climates where the oil is circulated for long periods at temperatures above 140°F., rapid oil oxidation may lead to troublesome sludging and wear in the system unless the oil is properly inhibited; whereas, at low temperatures high oil viscosity may prevent starting or satisfactory operation of hydraulic accessories.

Of course, every hydraulic system has inherent mechanical limitations. For example, pump slippage, cavitation, fluid and mechanical friction, and oil leakage are functions of mechanical clearances within pumps, valves, packings, etc., but an oil of the proper physical characteristics can minimize the effect of these clearances.

At low temperatures, viscosity and pour point are the characteristics which limit the usefulness of petroleum-base oils as hydraulic media. It is the purpose of this article to discuss the properties of petroleum-base hydraulic oils and the various elements of hydraulic circuits which affect low-temperature hydraulic operation.

VISCOSITY AND VISCOSITY INDEX

Oil viscosity is of great importance in hydraulic systems, particularly under conditions of laminar flow, because it influences such efficiency-limiting factors as:

1. Pump slippage
2. Mechanical and fluid friction
3. Pump cavitation
4. System leakage
5. Actuator and valve response rate

High viscosities reduce slippage of oil backward past pump clearances and also reduce leakage of oil through packings and tubing connections. On the other hand, high viscosities increase fluid friction and, therefore, encourage pump cavitation and sluggishness of actuating mechanisms in the system.

Low viscosities reduce fluid friction, while some minimum intermediate viscosity may be necessary to prevent rapid wear of sliding parts. Therefore, the selection of an oil viscosity, or viscosity range, for a particular hydraulic application must be based upon a compromise among efficiency of operation,

wear rate, and the rapidity with which the mechanisms operated by the hydraulic unit must be moved. Such a compromise can be evaluated only through experimentation on the system being considered.

Increasing the temperature of an oil decreases its viscosity. The rate of change of the viscosity of an oil with change in temperature may be expressed in terms of Viscosity Index*, or V.I. The less its change of viscosity with a change in temperature, the higher the V.I. an oil has. This is illustrated in Figure 2 where the viscosity-temperature lines for two oils of different V.I., but having in common a 150 Saybolt Universal seconds viscosity at 100°F., are shown. The 50-V.I. Oil A line has a greater slope than the 90-V.I. Oil B line.

The V.I. of an oil can be increased by refining techniques; and further by the addition of V.I.-improver additives, which are usually long-chain hydrocarbon polymers. However, for most present day hydraulic operations, except in aircraft, the additional cost of V.I.-improvers in hydraulic oils is not justified in terms of service performance.

Oils having good viscosity-temperature qualities are desirable in hydraulic systems which must operate over a wide ambient temperature range, so that easier low temperature starting and the maintenance of higher viscosities at high operating temperatures for better wear protection are assured. Substantial increases in V.I. must be effected, however, before benefits of practical significance can be realized. For example, it can be seen in Figure 2 that the 90-V.I. oil will allow starting at a temperature only 5°F. lower than the 50-V.I. oil if 4000 Saybolt Universal seconds is not to be exceeded. Further, at 210°F., which is definitely on the hot side for hydraulic systems, the viscosity of the 90-V.I. oil exceeds that of the lower V.I. oil by little more than one Saybolt Universal second.

The viscosity-temperature curves of Figure 2 are usually drawn from the 100 and 210°F. viscosity values. These may be extrapolated as a straight line to low temperatures approaching the pour point as long as the oil has not been treated with V.I.-improver additives or pour point depressants, which may make the line deviate unpredictably from the straight.

Slightly above the pour temperature of a wax-containing oil, the precipitating wax may form a crystal structure which is firm enough to make the viscosity of the oil, as measured by the Saybolt cup method (i.e., under low shear conditions), increase more rapidly than would be predicted by a straight extension of the A.S.T.M. viscosity-temperature line in the low temperature direction. If, however, a pour point depressant material is added to the oil, the formation of the wax crystal structure is hindered and the viscosities in the vicinity of the original pour point temperature are thereby lowered. Thus, the temperature range over which the oil is pumpable may be extended.

* For a more detailed discussion on Viscosity Index, see "Viscosity", Magazine LUBRICATION, May and June 1950.

Courtesy Bucyrus-Erie Company

Figure 1 — A Hydraulically Operated Bulldozer Converting a British Columbia Forest into Farm Land in Cold Weather.

It should be realized that the viscosity of an oil increases when it is subjected to pressure in a hydraulic system. For example, a paraffinic oil similar to present day straight mineral 150 Saybolt Universal seconds viscosity hydraulic oil had a 167-second viscosity at atmospheric pressure and 100°F., a 277-second viscosity at 2920 p.s.i., and a 730-second viscosity at 9900 p.s.i. With modern hydraulic systems operating in the vicinity of 6000 p.s.i. or above, the pressure-viscosity relationship will be significant enough to increase friction losses in the pressure side of the system, thereby limiting the speed with which hydraulic mechanisms may be actuated.

Generally, the following statements cover the effect of pressure on the viscosity of mineral oils:

1. A unit increase in pressure has more effect on viscosity at high pressures than at low pressures.
2. The viscosity of paraffin-base oils is generally affected less than that of naphthenic-base oils by a unit pressure increase.
3. The lower the viscosity of an oil, within the viscosity range normally used in hydraulic systems, the less effect a unit increase of pressure will have on its viscosity.

POUR POINT

According to the A.S.T.M. Standard Method of Test for Cloud and Pour Points (A.S.T.M. Designation: D-97), th pour point of a petroleum oil is the lowest temperature at which the oil will pour or flow when it is chilled without disturbance under definite prescribed conditions. "Viscosity pour point", as in the case of wax-free oils, represents the temperature at which the viscosity is so high that further cooling with the attendant further increase in viscosity causes flow to stop. "Wax pour point" marks the temperature at which crystallization of wax has proceeded to the extent that further lowering of temperature causes oil flow to stop.

The pour point of an oil is dependent upon the previous thermal history of the oil, and upon the rate of cooling to the pour temperature. Rapid cooling, for example, causes a fine crystalline structure with a resultant lower pour point than if the oil had been cooled slowly.

It is for the above reason that the pour point determination is carried out under carefully-prescribed conditions of preheating the oil sample (to eliminate any partial crystallization of wax) followed by cooling in baths of specified temperature until the pour point is reached. The pour point itself is recognizable by the fact that no movement of the oil occurs when the glass test jar is turned on its side for 5 seconds. The pour temperature is recorded to the nearest 5°F. increment.

Referring to Figure 2, it might be expected that the pour point temperature of an oil would correspond to some specific viscosity value on the viscosity-temperature line. However, it should be recalled from the above discussion on "Viscosity and Viscosity Index" that this line does not, except in the case of wax-free oils, hold true in the vicinity of the pour point. Instead, viscosity swings up sharply with the precipitation of wax.

In view of the above, it is apparent that pour point has no direct relation to the low temperature pumpability of a hydraulic oi' Pour point can only serve as a guide to the temperature at which an oil will no longer feed to the pump from the reservoir, or will jam up the pressure side of the system. Generally, it is recommended that the pour point of a hydraulic oil be at least 15°F. below the lowest temperature to which the system will be subjected.

SPECIFIC GRAVITY

The specific gravity of a hydraulic oil determines the static pressure or suction head between the oil reservoir and pump, and therefore affects the operation of the system. However, since the specific gravi-

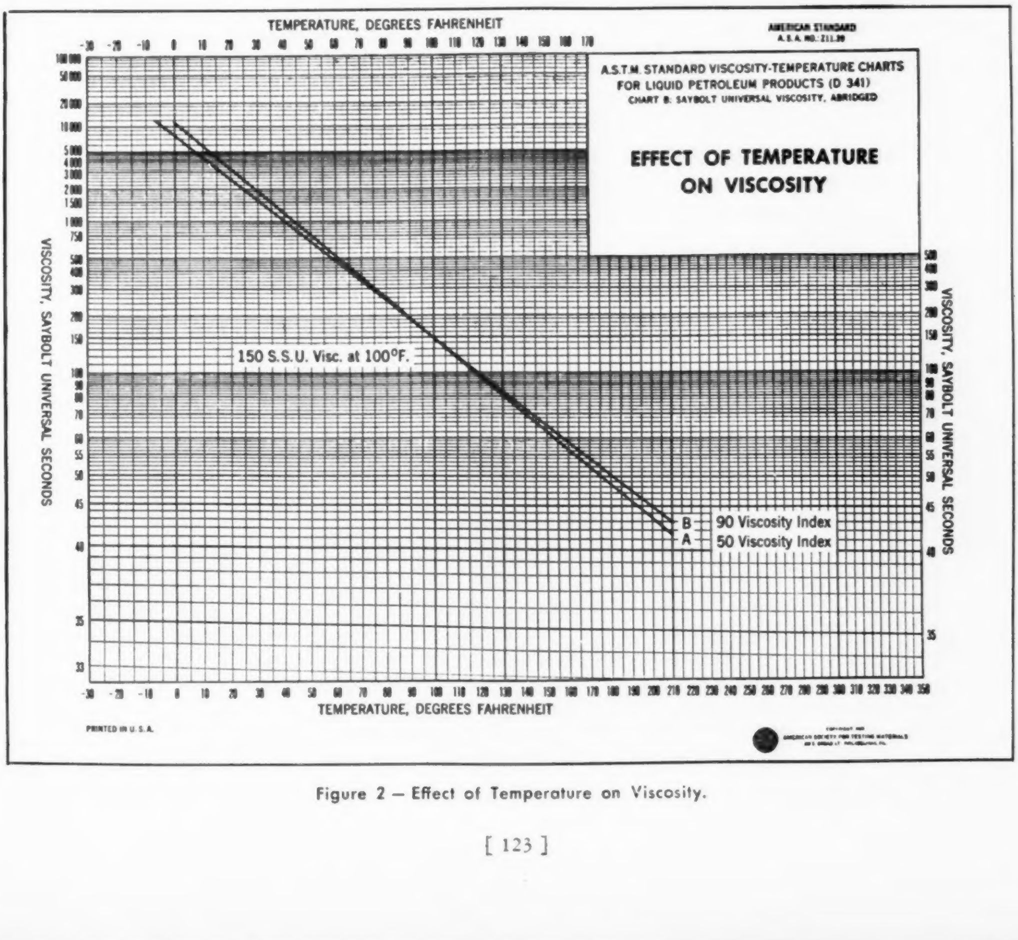


Figure 2 — Effect of Temperature on Viscosity.

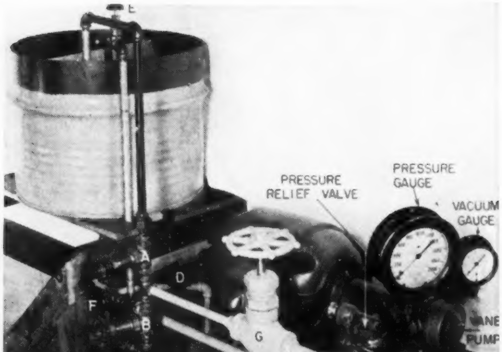


Figure. 3 — Vane-Pump Low Temperature Test Apparatus.

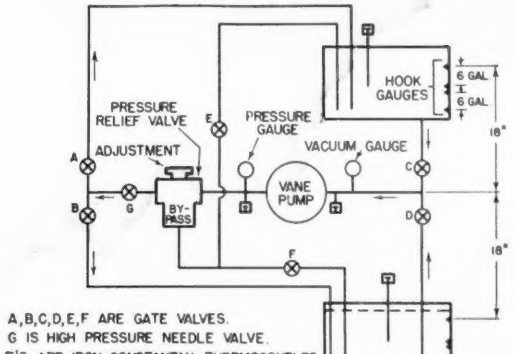


Figure 4 — Schematic Diagram of Vane-Pump Test Apparatus.

ties of petroleum-base hydraulic oils range between the rather narrow limits of 0.86 and 0.92 at 60°F. (as compared to the density of water at 60°F.), specific gravity may be neglected as a point of comparison between oils for hydraulic systems. An oil level one foot above the pump inlet ports will exert a positive static oil pressure of about 0.4 p.s.i. at the inlet.

VANE-PUMP TESTS AT LOW TEMPERATURES

The suction developed by a vane, gear or piston pump may not be sufficient to draw a cold, highly viscous fluid into a hydraulic system steadily and smoothly, thus giving rough and sluggish operation of the system.

The results of a laboratory study of the effect of oil viscosity upon the operating efficiency of vane-type pumps are described below:

Test Equipment

The test apparatus, pictured in Figure 3 and illustrated schematically in Figure 4, consisted of a double-acting vane pump driven at 1740 RPM to give a theoretical delivery of 7.8 gallons per minute, with the necessary piping and valves to allow pumping from either reservoir.

Valve "G" was used in conjunction with the pressure gage to produce the desired pressure at the pump outlet, while the relief valve prevented the application of excessive pressure. A range of test viscosities was provided by varying the temperature of the apparatus and oil in a temperature-controlled room.

The oil reservoirs were located so that, when used to feed the pump, the starting oil level of one was 18 inches above the pump centerline, while that of the second one was 18 inches below the centerline. These represent the usual extremes in reservoir oil levels encountered in service. The vacuum gage near the pump inlet registered the suction developed by the pump while in operation.

The pipe and fittings from the upper reservoir to the pump inlet were equivalent to approximately 8 feet of one-inch iron pipe, while the pipe and fittings from the bottom reservoir were equivalent to approximately 13 feet of one-inch iron pipe. Therefore, the positive static oil head as well as the lesser amount of pipe friction between the upper reservoir and the pump inlet was more favorable to pump operation than the conditions offered by the lower reservoir, as will be illustrated later on.

One pump manufacturer recommends that the pipe or tubing leading into the pump inlet ports be straight for at least 20 pipe diameters to assure laminar flow into the pump. However, the test apparatus had a 90-degree elbow only three diameters from the pump housing inlet, which is typical of many systems in actual practice.

Oils Tested

Five oils typical of those used in hydraulic service but of widely varying characteristics were used in the pump tests, and are described in Table I.

Test Procedure

For a test run, the reservoir to be used as the pump feed tank was filled with oil, and then the apparatus and oil temperatures were brought to the desired test temperature in the temperature-controlled room. Two pairs of hooks placed in a vertical line inside the reservoirs, used in conjunction with a stopwatch, allowed flow rates to be measured at two successive outlet pressures. The test temperatures for each oil were lowered in increments until loud pump noise and greatly diminished flow rate occurred.

Pump noise level was evaluated by ear as being:

Zero = Low level of pump noise
a = Smooth whine, higher noise level
b = Whining, grating sound.

As is generally recognized in the hydraulic field, pump noise of the "a" and "b" categories is generated by cavitation.

Cavitation

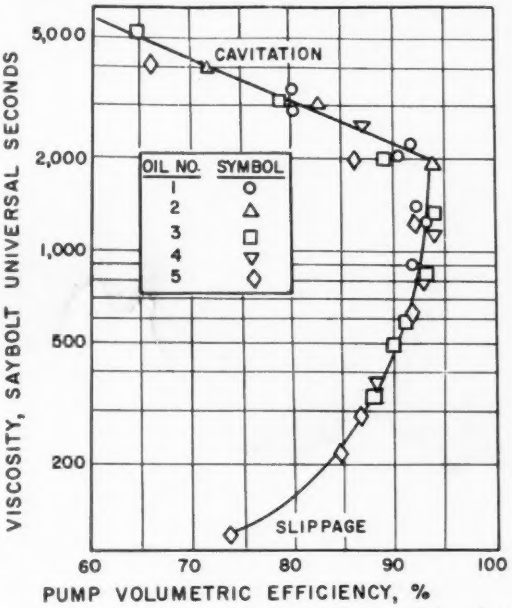
Cavitation in liquid-moving pumps occurs when the absolute pressure in the pump-inlet line drops enough below atmospheric to force dissolved gases out of solution, to vaporize lighter fractions of the liquid, or to draw air in through leaks in the inlet line. The resulting mechanically-entrained bubbles reduce pumping efficiency and cause mechanical vibrations due to sudden bubble collapse on the pressure side or pressure stroke of the pump. These mechanical vibrations produce objectionable noise and may also fatigue and erode pump parts.

In the case of petroleum oils at low temperatures, vaporization of the lighter oil fractions is not a factor in cavitation because of their extremely low vapor pressures. However, it has been shown that air solubility in petroleum oils is in the vicinity of 10 per cent by volume at 32°F. and slightly greater at lower temperatures. Therefore, serious cavitation is imminent at low temperatures (high viscosities) if pump inlet line pressure-drop becomes severe enough to pull large volumes of air out of its oil solution. Typical manufacturers' recommendations for maximum permissible vacuum at the pump inlet with petroleum oils are 5 p.s.i. for vane-type pumps and 7.5 p.s.i. for gear-type pumps.

Test Results

Oil flow in the test pump inlet and outlet lines was essentially viscous, except for possible localized turbulence caused by pipe fittings, since the calculated Reynolds Numbers were below 1500 in all cases.

The heating effect of the pump on the oil was less than 2°F. because the test oil was not recirculated and because the short duration of each run did not give the pump a chance to warm up. Oil temperature rise through the inlet pipe lines due to pipe friction was negligible. Therefore, the pump was operated solely under starting conditions, with the oil viscosity throughout the system remaining for all practical purposes the same as that in the feed reservoir.



Courtesy Vickers, Inc.

Figure 5 — Effect of Viscosity on Vane-Pump Volumetric Efficiency at 1000 p.s.i. with Oil Feed Reservoir Below Pump.

The curve of Figure 5 is a typical plot of the data illustrating the effect of viscosity on the volumetric efficiency of the vane pump. In this case, the data points adhere particularly closely to the curve defined by them at the viscosity values below 1900 Saybolt seconds. Above this value, the rapid drop in pump efficiency reflects the onset of cavitation, and pump delivery becomes somewhat erratic, as reflected by scattering of the data points.

The curves of Figures 6 and 7 summarize all the volumetric efficiency-viscosity data. As shown in Figure 6 when the system was operated at essentially zero p.s.i. pump outlet pressures*, volumetric effi-

* "Zero p.s.i." is a nominal figure to represent operation with no load placed upon the system other than the pressure drop occurring in the piping between the pump outlet and the receiving reservoir. Pressure drops up to 95 p.s.i. were encountered in this phase of the work, depending upon viscosity and flow rate.

TABLE I
VANE-PUMP LOW TEMPERATURE TEST OILS

Oil No.	Oil and Type	Viscosity, Saybolt Universal Sec. At 32°F.	Viscosity, Saybolt Universal Sec. At 100°F.	Viscosity Index	ASTM D-97 Pour Point, °F.	Specific Gravity, 60/60°F.
1	Naphthenic, Non-Additive	13,700	493	25	−15	0.9175
2	Paraffinic, Contains Additives	1,400	153	98	−10	0.8648
3	Paraffinic, Contains Additives	17,500	953	95	5	0.8851
4	Paraffinic, Contains Additives	357	64.6	70	−60	0.8981
5	Paraffinic, Contains Additives	1,760	195	124	−25	0.8748

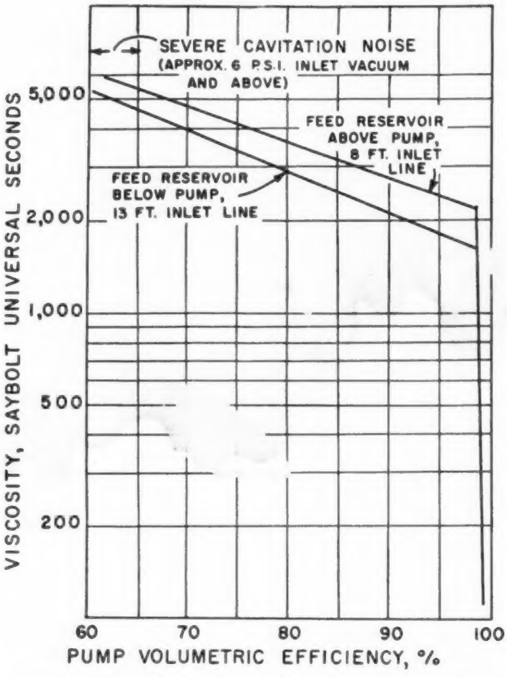


Figure 6 — Effect of Viscosity on Vane-Pump Volumetric Efficiency at 0 p.s.i. Pump Outlet Pressure.

ciency remained close to 100 per cent for oil viscosities ranging from 110 to 1700 Saybolt Universal seconds with the lower feed reservoir and the longer inlet line. Volumetric efficiency remained close to 100 per cent for viscosities ranging from 110 to 2200 Saybolt Universal seconds with the upper feed reservoir and the shorter inlet line. At viscosities exceeding the above ranges, rapid loss in volumetric efficiency occurred due to excessive cavitation which is made evident by the rapid drop of the efficiency curves. Viscosities below 110 seconds were not considered.

At 1000 p.s.i. pump outlet pressure, volumetric efficiency reached a peak for oil viscosities of 2700 Saybolt Universal seconds when pumping from the upper feed reservoir and 1900 Saybolt Universal seconds when pumping from the lower feed reservoir (See Figure 7). At viscosities exceeding those for maximum volumetric efficiency, the efficiencies dropped off sharply because of cavitation. At viscosities below those for peak volumetric efficiency, pump slippage encouraged by both the outlet pressure and the lower viscosities caused efficiency to drop.

It is noted on Figures 6 and 7 that severe (level "b") cavitation noise occurred at viscosities exceeding those for peak efficiency and that the severe noise level occurred at higher viscosities when the outlet pressure was zero instead of 1000 p.s.i. The reason for this phenomenon is that much of the noise occurring with cavitation is evolved with the collapse of the air bubbles on the pressure side of the pump. The 1000 p.s.i. operation increases the rapidity with which bubbles [illegible] given size and quantity collapse, thereby m[illegible] more noise. As viscosity (and therefore inlet vacuum) is increased further, the air bubbles become larger and more plentiful so that their collapse even at relatively low pumping pressures makes considerable noise.

It is logical to assume, of course, that some level of cavitation is always present in a hydraulic system if the hydraulic fluid contains dissolved air and if the inlet line to the pump offers resistance to oil flow, causing a pressure drop and the formation of air bubbles. In fact, a low level ("a" level) of cavitation was noted at viscosities below the knees of the efficiency curves of Figures 6 and 7.

The data discussed above illustrate that maximum pump volumetric efficiency is achieved with oil viscosities which keep the combined effects of cavitation and oil slippage backwards past the pump clearances at a minimum. Shorter inlet lines and positive feed oil heads allow viscosity to reach a higher level before pump efficiency drops off.

HYDRAULIC SYSTEM COMPONENTS AND LOW TEMPERATURE OPERATION

Of the hydraulic system design factors discussed above that have an effect upon pumping efficiency,

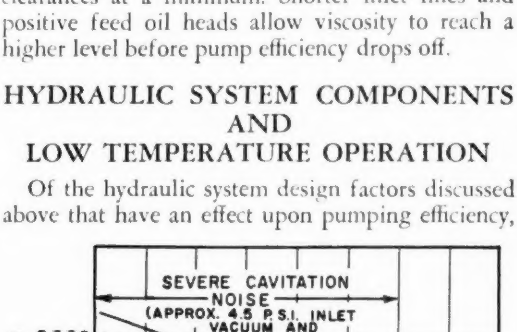


Figure 7 — Effect of Viscosity on Vane-Pump Volumetric Efficiency at 1000 p.s.i. Pump Outlet Pressure.

the following are of particular importance at low temperatures because they determine the maximum oil viscosities permissible for efficient operation:

1. Length and configuration of pump intake pipe.
2. Static head of oil in the feed reservoir relative to pump.

Other design and operational factors which limit the maximum tolerable viscosities for low temperature operation are discussed below.

Oil Reservoir

Figure 8 is an example of good reservoir design. The baffle plate segregates the oil returning to the reservoir from that being taken up by the pump. This allows the returning oil more time to separate out air as well as other contaminants before being picked up again by the pump.

Return and suction lines may enter the top or sides of the reservoir. In either case, however, the return pipe should be on one side of the baffle plate and the pump intake on the other. It is desirable to locate the ends of these pipes within about two pipe diameters of the reservoir bottom. The return should be low, for if it is near or above the oil level, the returning oil may cause foaming.

It is also important that the pump intake pipe opening be close to the bottom of the reservoir to prevent channelling of the oil around the intake pipe when the oil is extremely viscous, as well as to prevent the formation of a whirlpool around the intake pipe with lighter viscosities. Either phenomenon will allow air to be drawn into the pump along with the oil, causing pump cavitation and erratic system operation. One manufacturer recommends as a general rule that the oil level be at least 12 to 18 inches above the intake point to eliminate this effect.

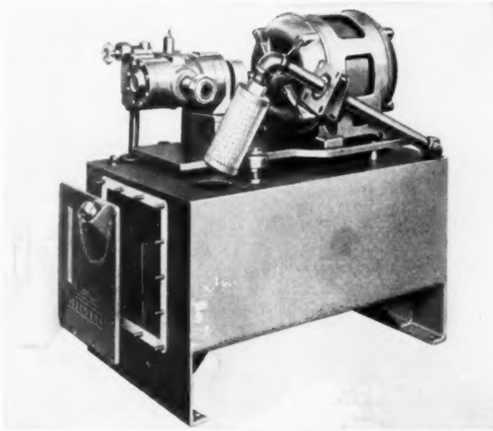
Adequate reservoir capacity—usually at least 2 to 3 times the rated pump delivery for one minute of operation — will insure that a sufficient height of oil is retained in the reservoir.

Where frequent low-temperature start-ups are anticipated, it may be advisable to equip the reservoir with heating coils or a heating jacket.

Oil Filters

Filters are located either on the pump intake pipe, as shown in Figure 8 or at some point in the system on the discharge side of the pump. They may be so installed that the full pump discharge passes through the filter or the filter may be so located that only a portion of the oil passes through the filter, the balance being by-passed.

Non-bypass filters present a low-temperature problem because they may impede oil flow through their small passages, especially if the passages are partially blocked with contaminants and oil deterioration products. Filters on the intake pipe may



Courtesy Vickers, Inc.

Figure 8 — Typical Hydraulic Reservoir. Note baffle plate separating incoming oil from that being picked up by the suction line. Also note typical suction line filter installation.

cause insufficient feed of viscous oil to the pump, while a non-bypass filter on the discharge side of the pump may cause large pressure drops followed by possible collapse or channelling of the filter cartridge.

One manufacturer of construction equipment provides for low temperature start-up with a hand-controlled bypass line around the filter mounted in the intake line. After the oil in the system has warmed up, the full oil flow is routed through the filter.

Pump Speed

An important variable which affects pumping efficiency strongly as viscosity increases is the speed at which the pump is operated. As a pump of given size and design is speeded up, it becomes less efficient and tends to cavitate with high viscosity oils because of the friction losses in pump inlet ports or valves. Reduced pump speeds for starting up a cold system may be achieved in practice by intermittently turning the pump drive motor on and off until the oil in the system is partially warmed and flowing properly.

Restrictions on the Pressure Side of the Hydraulic System

The rapidity with which hydraulic mechanisms can be moved is largely dependent upon viscosity. Unexpectedly large pressure drops occur through tubing, valves and other restrictions in the pressure side of hydraulic systems because of the appreciable effect of pressure upon viscosity. If the viscosity is further increased because of low operating temperatures, these pressure drops reduce the net pressure available at the hydraulic cylinder or other device to be actuated to the extent that operation becomes sluggish.

MANUFACTURERS' VISCOSITY RECOMMENDATIONS

To meet the demands of the many hydraulic pump manufacturers, quite a number of viscosity grades of hydraulic oil are supplied by the petroleum industry. However, it has been shown that any petroleum oil's viscosity fluctuates with temperature change. Therefore, unless the operating temperature of the hydraulic system is closely controlled, a pump manufacturer's viscosity recommendation is a compromise that will give the most satisfactory over-all performance in his equipment, based on efficiency, wear-resistance, and the oils available.

The usual practice of hydraulic manufacturers is to specify hydraulic oils on the basis of the 100°F. viscosity in Saybolt Universal seconds or on the basis of an SAE grade in the case of some construction or farm machinery.

To cover low-temperature starting conditions a maximum permissible viscosity or pour point may also be specified. Where the equipment must be adaptable to extremes of weather, a second lighter grade oil may be specified for cold weather operation.

On the other hand, dilution of the warm weather oil with kerosine may be recommended as a temporary expedient for cold weather operation. Kerosine lowers the pour point as well as the viscosity of the treated oil. To illustrate the effects of kerosine dilution, Oil No. 1 (see Table I) was cut back with various amounts of kerosine and then tested for viscosity and pour point. The results of this investigation are given in Table II.

TABLE II
EFFECT OF KEROSINE ON VISCOSITY AND POUR POINT OF A NAPHTHENIC HYDRAULIC OIL

Volume % Of Kerosine In Oil 1	Viscosity, SUS At 0°F.	Viscosity, SUS At 32°F.	Viscosity, SUS At 100°F.	ASTM D-97 Pour Point, °F.
None	Over 100,000	13,700	493	−15
15	18,000	2,150	165	−30
30	2,200	490	77	−45
50	400	135	48	−55

The ASTM Viscosity-Temperature Chart furnishes a convenient method for estimating the viscosity at a given temperature of blends of petroleum liquids, if viscosities of the component liquids at the given temperature are known. For this purpose, the 0°F. line on the ASTM Chart is used to represent 100 per cent by volume of the lower viscosity component, and the 100°F. line to represent 100 per cent by volume of the higher viscosity component.

An illustration of this method of estimating the viscosity of a blend is given in Figure 9 for 30 per cent kerosine and 70 per cent Oil No. 1 at 32°F. In this case, the line joining the viscosities

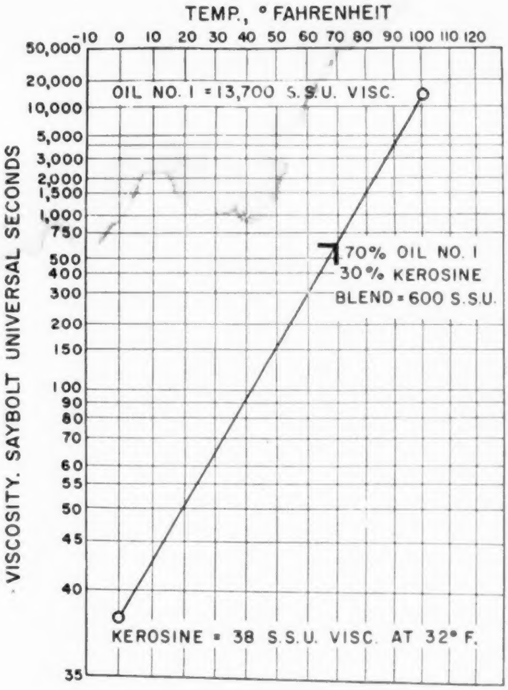


Figure 9 — Viscosity Estimation of Kerosine-Hydraulic Oil Blend.

of the kerosine and Oil No. 1 crosses the 70 per cent (70°F.) line at 600 Saybolt Universal seconds. As shown in Table II, the actual viscosity of this blend at 32°F. is 490 Saybolt Universal seconds, indicating that the approximation from the ASTM Chart is useful for practical purposes, though not highly accurate in this case. The discrepancies between actual and estimated viscosities by this method increase with the difference in viscosity of the two components being blended.

CONCLUSION

Modern hydraulic pumps and valves are precisely made. Their close fits are necessary to maintain the high pressures encountered in hydraulic systems. Therefore, to allow hydraulic machinery to operate at its best efficiency, as well as to resist wear and deposit formation, hydraulic systems should be supplied only with high quality oil of the viscosity grade recommended by the equipment manufacturer. Hydraulic systems that must be started up at unusually low temperatures require oils of sufficiently low viscosity and pour point to assure adequate oil feed to the pump while the oil is cold. Hydraulic oils having high viscosity indices give the most assurance of good low temperature starting characteristics combined with adequate lubrication and a minimum of pump slippage at higher temperatures.

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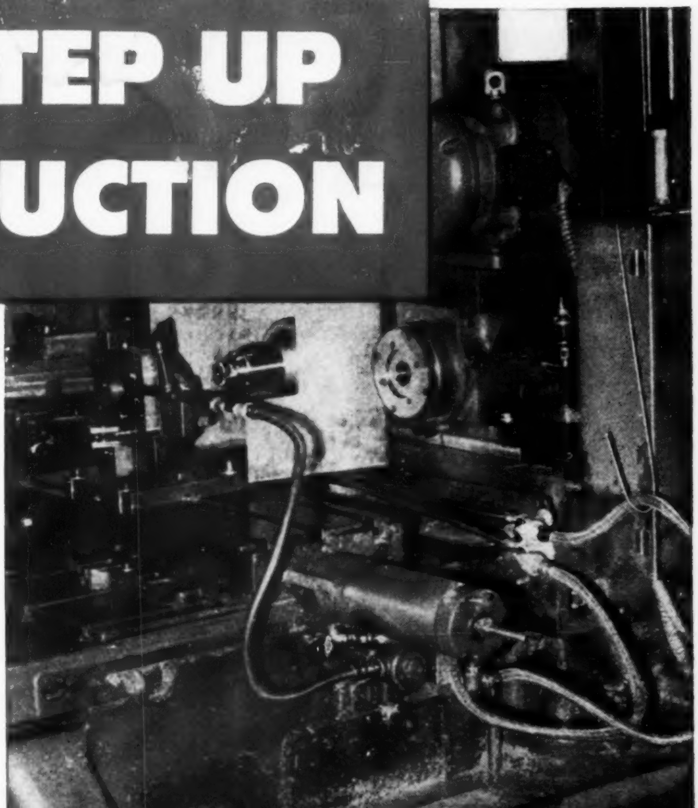

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